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Novel Aspects of QCD in Leptoproduction*

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Abstract

I review several topics in electroproduction which test fundamental aspects of QCD. These include the role of final-state interactions in producing diffractive leptoproduction processes, the shadowing of nuclear structure functions, and target-spin asymmetries. The antishadowing of nuclear structure functions is shown to be quark-flavor specific, suggesting that some part of the anomalous NuTeV result for $\sin^2\theta_W$ could be due to the non-universality of nuclear antishadowing for charged and neutral currents. I also discuss the physics of the heavy-quark sea, hidden color in nuclear wavefunctions, and evidence for color transparency for nuclear processes. The AdS/CFT correspondence connecting superstring theory to superconformal gauge theory has important implications for hadron phenomenology in the conformal limit, including an all-orders demonstration of counting rules for hard exclusive processes, as well as determining essential aspects of hadronic light-front wavefunctions.

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1 Introduction

Although it has been more than 35 years since the discovery of Bjorken scaling [1] in electroproduction [2], there are still many issues in deep-inelastic lepton scattering that are only now are being understood from a fundamental basis in quantum chromodynamics. This includes the role of final-state interactions in producing diffractive leptoproduction processes, the shadowing of nuclear structure functions, and target spin asymmetries. As I will discuss, the antishadowing of nuclear structure functions is quark-flavor specific; this implies that part of the anomalous NuTeV [3] result for $\sin^2\theta_W$ could be due to the non-universality of nuclear antishadowing for charged and neutral currents. I also discuss the physics of the heavy-quark sea, hidden color, and the role of conformal symmetry in hard exclusive processes. The AdS/CFT correspondence connecting superstring theory to superconformal gauge theory has important implications for hadron phenomenology in the conformal limit, including an all-orders demonstration of counting rules for hard exclusive processes, as well as determining essential aspects of hadronic light-front wavefunctions.

2 Complications from Final-State Interactions

It is usually assumed—following the parton model—that the leading-twist structure functions measured in deep inelastic lepton-proton scattering are simply the probability distributions for finding quarks and gluons in the target nucleon. In fact, gluon exchange between the fast, outgoing quarks and the target spectators effects the leading-twist structure functions in a profound way, leading to diffractive leptoproduction processes, shadowing of nuclear structure functions, and target spin asymmetries. In particular, the final-state interactions from gluon exchange lead to single-spin asymmetries in semi-inclusive deep inelastic lepton-proton scattering which are not power-law suppressed in the Bjorken limit.

A new understanding of the role of final-state interactions in deep inelastic scattering has recently emerged [4]. The final-state interactions from gluon exchange between the outgoing quark and the target spectator system lead to single-spin asymmetries (the Sivers effect) in semi-inclusive deep inelastic lepton-proton scattering at leading twist in perturbative QCD; *i.e.*, the rescattering corrections of the struck quark with the target spectators are not power-law suppressed at large photon virtuality Q^2 at fixed x_{bj} [5]. The final-state interaction from gluon exchange occurring immediately after the interaction of the current also produces a leading-twist diffractive component to deep inelastic scattering $\ell p \to \ell' p' X$ corresponding to color-singlet exchange with the target system; as discussed below, this in turn produces shadowing and anti-shadowing of the nuclear structure functions [4, 6]. In addition, Paul Hoyer, Gunnar Ingelman, Rikard Enberg and I have shown that the pomeron structure function derived from diffractive DIS has the same form as the quark contribution of the gluon structure function [7]. This is discussed in more detail in Paul Hoyer's contribution to these proceedings.

The final-state interactions occur at a light-cone time $\Delta\tau \simeq 1/\nu$ after the virtual photon interacts with the struck quark, producing a nontrivial phase. Thus none of the above phenomena is contained in the target light-front wave functions computed in isolation. In particular, the shadowing of nuclear structure functions is due to destructive interference effects from leading-twist diffraction of the virtual photon, physics not included in the nuclear light-front wave functions. Thus the structure functions measured in deep inelastic lepton scattering are affected by final-state rescattering, modifying their connection to light-front probability distributions. Some of these results can be understood by augmenting the light-front wave functions with a gauge link, but with a gauge potential created by an external field created by the virtual photon $q\bar{q}$ pair current [8]. The gauge link is also process dependent [9], so the resulting augmented LFWFs are not universal.

3 The Origin of Nuclear Shadowing and Antishadowing

The shadowing and antishadowing of nuclear structure functions in the Gribov-Glauber picture is due respectively to the destructive and constructive interference of amplitudes arising from the multiple-scattering of quarks in the nucleus. The effective quark-nucleon scattering amplitude includes Pomeron and Odderon contributions from multi-gluon exchange as well as Reggeon quark-exchange contributions [6]. The coherence of these multiscattering nuclear processes leads to shadowing and antishadowing of the electromagnetic nuclear structure functions in agreement with measurements. Recently, Ivan Schmidt, Jian-Jun Yang, and I [10] have shown that this picture leads to substantially different antishadowing for charged and neutral current reactions, thus affecting the extraction of the weak-mixing angle $\sin^2\theta_W$. We find that part of the anomalous NuTeV result for $\sin^2\theta_W$ could be due to the non-universality of nuclear antishadowing for charged and neutral currents. Detailed measurements of the nuclear dependence of individual quark structure functions are thus needed to establish the distinctive phenomenology of shadowing and antishadowing and to make the NuTeV results definitive.

4 Light-Front Wavefunctions in QCD

The concept of a wave function of a hadron as a composite of relativistic quarks and gluons is naturally formulated in terms of the light-front Fock expansion at fixed light-front time, $\tau = x \cdot \omega$. The four-vector ω, with $\omega^2 = 0$, determines the orientation of the light-front plane; the freedom to choose ω provides an explicitly covariant formulation of light-front quantization [11]. The light-front wave functions (LFWFs)

$\psi_n(x_i, k_{\perp_i}, \lambda_i)$, with $x_i = \frac{k_i \cdot \omega}{P \cdot \omega}$, $\sum_{i=1}^n x_i = 1$, $\sum_{i=1}^n k_{\perp_i} = 0_\perp$, are the coefficient functions for n partons in the Fock expansion, providing a general frame-independent representation of the hadron state.

Light-front quantization in the doubly-transverse light-cone gauge [12, 13] has a number of advantages, including explicit unitarity, a physical Fock expansion, exact representations of current matrix elements, and the decoupling properties needed to prove factorization theorems in high momentum transfer inclusive and exclusive reactions.

Matrix elements of local operators such as spacelike proton form factors can be computed simply from the overlap integrals of light front wave functions in analogy to nonrelativistic Schrödinger theory. For example, one can derive exact formulae for the weak decays of the B meson such as $B \to \ell \bar{\nu} \pi$ [14] and the deeply virtual Compton amplitude (DVCS) in the handbag approximation [15, 16]. An interesting aspect of DVCS is the prediction from QCD of a $J = 0$ fixed Regge pole contribution to the real part of the Compton amplitude which has constant energy $s^0 F(t)$ dependence at any momentum transfer t or photon virtuality [17, 18]. It arises from the quasi-local coupling of two photons to the quark current arising from the quark Z-graph in time-ordered perturbation theory of the instantaneous quark propagator arising in light-front quantization.

One can also define [19] a light-front partition function Z_{LF} as an outer product of light-front wavefunctions. The deeply virtual Compton amplitude and generalized parton distributions can then be computed as the trace $Tr[Z_{LF}\mathcal{O}]$, where $\mathcal{O}$ is the appropriate local operator. This partition function formalism can be extended to multi-hadronic systems and systems in statistical equilibrium to provide a Lorentz-invariant description of relativistic thermodynamics [19].

Other applications include two-photon exclusive reactions, and diffractive dissociation into jets. The universal light-front wave functions and distribution amplitudes control hard exclusive processes such as form factors, deeply virtual Compton scattering, high momentum transfer photoproduction, and two-photon processes.

One of the central issues in the analysis of fundamental hadron structure is the presence of non-zero orbital angular momentum in the bound-state wave functions. The evidence for a "spin crisis" in the Ellis-Jaffe sum rule signals a significant orbital contribution in the proton wave function [20, 21]. The Pauli form factor of nucleons is computed from the overlap of LFWFs differing by one unit of orbital angular momentum $\Delta L_z = \pm 1$. Thus the fact that the anomalous moment of the proton is non-zero requires nonzero orbital angular momentum in the proton wavefunction [22]. In the light-front method, orbital angular momentum is treated explicitly; it includes the orbital contributions induced by relativistic effects, such as the spin-orbit effects normally associated with the conventional Dirac spinors.

A number of new non-perturbative methods for determining light-front wave functions have been developed including discretized light-cone quantization using Pauli-Villars regularization, supersymmetry, and the transverse lattice. One can also project the known solutions of the Bethe-Salpeter equation to equal light-front time, thus producing hadronic light-front Fock wave functions. A potentially important method is to construct the $q\bar{q}$ Green's function using light-front Hamiltonian theory, with DLCQ boundary conditions and Lippmann-Schwinger resummation. The zeros of the resulting resolvent projected on states of specific angular momentum J_z can then generate the meson spectrum and their light-front Fock wavefunctions. For a recent review of light-front methods and references, see Ref. [23].

Diffractive multi-jet production in heavy nuclei provides a novel way to measure the shape of light-front Fock state wave functions and test color transparency [24]. For example, consider the reaction [25, 26] $\pi A \to \mathrm{Jet}_1 + \mathrm{Jet}_2 + A'$ at high energy where the nucleus A' is left intact in its ground state. The transverse momenta of the jets balance so that $\vec{k}_{\perp i} + \vec{k}_{\perp 2} = \vec{q}_\perp < R^{-1}{}_A$. The light-cone longitudinal momentum fractions also need to add to $x_1 + x_2 \sim 1$ so that $\Delta p_L < R_A^{-1}$. The process can then occur coherently in the nucleus. Because of color transparency, the valence wave function of the pion with small impact separation, will penetrate the nucleus with minimal interactions, diffracting into jet pairs [25]. The $x_1 = x$, $x_2 = 1 - x$ dependence of the di-jet distributions will thus reflect the shape of the pion valence light-cone wave function in x; similarly, the $\vec{k}_{\perp 1} - \vec{k}_{\perp 2}$ relative transverse momenta of the jets gives key information on the derivative of the underlying shape of the valence pion wavefunction [26, 27]. The diffractive nuclear amplitude extrapolated to $t = 0$ should be linear in nuclear number A if color transparency is correct. The integrated diffractive rate should then scale as $A^2/R_A^2 \sim A^{4/3}$ as verified by E791 for 500 GeV incident pions on nuclear targets [28]. The measured momentum fraction distribution of the jets is consistent with the shape of the pion asymptotic distribution amplitude, $\phi_\pi^{\mathrm{asympt}}(x) = \sqrt{3} f_\pi x(1-x)$ [29]. Data from CLEO [30] for the $\gamma\gamma^* \to \pi^0$ transition form factor also favor a form for the pion distribution amplitude close to the asymptotic solution to its perturbative QCD evolution equation [31, 32, 33].

5 Heavy Quark Components of the Proton Structure Function

In the simplest treatment of deep inelastic scattering, nonvalence quarks are produced via gluon splitting and DGLAP evolution. However, in a full theory heavy quarks are multiply-connected to the valence quarks [34]. For example, the asymmetry of the strange and anti-strange distributions in the nucleon is due to their different interactions with the other quark constituents. The probability for Fock states of a light hadron such as the proton to have an extra heavy quark pair decreases as $1/m_Q^2$ in non-Abelian gauge theory [35, 36]. The relevant matrix element is the cube of the QCD field strength $G^3_{\mu n u}$. This is in contrast to abelian gauge theory where the relevant operator is $F^4_{\mu\nu}$ and the probability of intrinsic heavy leptons in QED bound state is suppressed as $1/m_\ell^4$. The intrinsic Fock state probability is maximized at minimal off shellness. The maximum probability occurs at $x_i = m^i_\perp / \sum_{j=1}^n m^j_\perp$; i.e., when the constituents have equal rapidity. Thus the heaviest constituents have the highest momentum fractions and highest x. Intrinsic charm thus predicts that the charm structure function has support at large x_{bj} in excess of DGLAP extrapolations [34]; this is in agreement with the EMC measurements [37]. It predicts leading charm hadron production and fast charmonium production in agreement with measurements [38]. The production cross section for the double charmed Ξ^+_{cc} baryon [39] and the production of double $J/\psi's$ appears to be consistent with the dissociation and coalescence of double IC Fock states [40]. Intrinsic charm can also explain the $J/\psi \to \rho\pi$ puzzle [41]. It also affects the extraction of suppressed CKM matrix elements in B decays [42]. It is thus critical for new experiments (HERMES, HERA, COMPASS) to definitively establish the phenomenology of the charm structure function at large x_{bj}.

6 The Role of Conformal Symmetry in QCD Phenomenology

The classical Lagrangian of QCD for massless quarks is conformally symmetric. Since it has no intrinsic mass scale, the classical theory is invariant under the $SO(4,2)$ translations, boosts, and rotations of the Poincare group, plus the dilatations and other transformations of the conformal group. Scale invariance and therefore conformal symmetry is destroyed in the quantum theory by the renormalization procedure which introduces a renormalization scale as well as by quark masses. Conversely, Parisi [43] has shown that perturbative QCD becomes a conformal theory for $\beta \to 0$ and zero quark mass. Conformal symmetry is thus broken in physical QCD; nevertheless, we can still recover the underlying features of the conformally invariant theory by evaluating any expression in QCD in the analytic limit of zero quark mass and zero β function:

$$\lim_{m_q \to 0, \beta \to 0} \mathcal{O}_{QCD} = \mathcal{O}_{\text{conformal QCD}} \ . \tag{1}$$

This conformal correspondence limit is analogous to Bohr's correspondence principle where one recovers predictions of classical theory from quantum theory in the limit of zero Planck constant. The contributions to an expression in QCD from its nonzero β-function can be systematically identified [44, 45, 46] order-by-order in perturbation theory using the Banks-Zaks procedure [47].

There are a number of useful phenomenological consequences of near conformal behavior of QCD: the conformal approximation with zero β function can be used as template for QCD analyses [48, 49] such as the form of the expansion polynomials for distribution amplitudes [50, 51]. The near-conformal behavior of QCD is the basis for commensurate scale relations [52] which relate observables to each other without renormalization scale or scheme ambiguities [44, 45]. By definition, all contributions from the nonzero β function can be incorporated into the QCD running coupling $\alpha_s(Q)$ where Q represents the set of physical invariants. Conformal symmetry thus provides a template for physical QCD expressions. For example, perturbative expansions in QCD for massless quarks must have the form

$$\mathcal{O} = \sum_{n=0} C_n \alpha_s^n(Q_n^*) \tag{2}$$

where the C_n are identical to the expansion coefficients in the conformal theory, and Q_n^* is the scale chosen to resum all of the contributions from the nonzero β function at that order in perturbation theory. Since the conformal theory does not contain renormalons, the C_n do not have the divergent n growth characteristic of conventional PQCD expansions evaluated at a fixed scale.

7 AFS/CFT Correspondence and Hadronic Light-Front Wavefunctions

As shown by Maldacena [53], there is a remarkable correspondence between large N_C supergravity theory in a higher dimensional anti-de Sitter space and supersymmetric QCD in 4-dimensional space-time. String/gauge duality provides a framework for predicting QCD phenomena based on the conformal properties of the AdS/CFT correspondence.

The AdS/CFT correspondence is based on the fact that the generators of conformal and Poincare transformations have representations on the five-dimensional anti-deSitter space AdS_5 as well as Minkowski spacetime. For example, Polchinski and Strassler [54] have shown that the power-law fall-off of hard exclusive hadron-hadron scattering amplitudes at large momentum transfer can be derived without the use of perturbation theory by using the scaling properties of the hadronic interpolating fields in the large-r region of AdS space. Thus one can use the Maldacena correspondence to compute the leading power-law behavior of exclusive processes such as high-energy fixed-angle scattering of gluonium-gluonium scattering in supersymmetric QCD. The resulting predictions for hadron physics effectively coincide [54, 55, 56] with QCD dimensional counting rules:[57, 58, 59]

$$\frac{d\sigma}{dt}(H_1 H_2 \to H_3 H_4) = \frac{F(t/s)}{s^{n-2}} \tag{3}$$

where n is the sum of the minimal number of interpolating fields in the initial and final state. (For a recent review of hard fixed θ_{CM} angle exclusive processes in QCD see reference [60].) Polchinski and Strassler [54] have also derived counting rules for deep inelastic structure functions at $x \to 1$ in agreement with perturbative QCD predictions [33, 61] as well as Bloom-Gilman exclusive-inclusive duality [62].

The supergravity analysis is based on an extension of classical gravity theory in higher dimensions and is nonperturbative. Thus analyses of exclusive processes [33] which were based on perturbation theory can be extended by the Maldacena correspondence to all orders. An important point is that the hard scattering amplitudes which are normally or order α_s^p in PQCD appear as order $\alpha_s^{p/2}$ in the supergravity predictions. This can be understood as an all-orders resummation of the effective potential [53, 63].

The superstring theory results are derived in the limit of a large N_C [64]. For gluon-gluon scattering, the amplitude scales as $1/N_C^2$. For color-singlet bound states of quarks, the amplitude scales as $1/N_C$. This large N_C-counting, in fact, corresponds to the quark interchange mechanism [65]. For example, for $K^+p \to K^+p$ scattering, the u-quark exchange amplitude scales approximately as $\frac{1}{u}\ \frac{1}{t^2}$, which agrees remarkably well with the measured large θ_{CM} dependence of the K^+p differential cross section [66]. This implies that the nonsinglet Reggeon trajectory asymptotes to a negative integer [67], in this case, $\lim_{-t\to\infty}\alpha_R(t) \to -1$.

De Teramond and I have extended the Polchinski-Strassler analysis to hadron-hadron scattering [68]. We have also shown how to compute the form and scaling of light-front hadronic wavefunctions using the AdS/CFT correspondence in quantum field theories which have an underlying conformal structure, such as $\mathcal{N} = 4$ superconformal QCD. For example, baryons are included in the theory by adding an open string sector in $AdS_5 \times S^5$ corresponding to quarks in the fundamental representation of the $SU(4)$ symmetry defined on S^5 and the fundamental and higher representations of $SU(N_C)$. The hadron mass scale is introduced by imposing boundary conditions at the AdS_5 coordinate $r = r_0 = \Lambda_{QCD}R^2$. The quantum numbers of the lowest Fock state of each hadron, including its internal orbital angular momentum and spin-flavor symmetry, are identified by matching the fall-off of the string wavefunction $\Psi(x, r)$ at the asymptotic $3+1$ boundary. Higher Fock states are identified with conformally invariant quantum fluctuations of the bulk geometry about the AdS background. The eigenvalues of the 10-dimensional Dirac and Rarita-Schwinger equations have also been used to determine the nucleon and Δ spectrum in conformal QCD. The results are in surprising agreement with the empirical spectra [69].

The scaling and conformal properties of the AdS/CFT correspondence leads to a hard component of light-front wavefunctions of the form [68]:

$$\begin{aligned}\psi_{n/h}(x_i, \vec{k}_{\perp i}, \lambda_i, l_{zi}) \ &\sim\ \frac{(g_s\ N_C)^{\frac{1}{2}(n-1)}}{\sqrt{N_C}} \prod_{i=1}^{n-1} (k_{i\perp}^{\pm})^{|l_{zi}|} \\ &\times\ \left[\frac{\Lambda_o}{M^2 - \sum_i \frac{\vec{k}_{\perp i}^2 + m_i^2}{x_i} + \Lambda_o^2}\right]^{n+|l_z|-1} ,\end{aligned} \tag{4}$$

where g_s is the string scale and Λ_o represents the basic QCD mass scale. The scaling predictions agree with perturbative QCD analyses [70, 33], but the AdS/CFT analysis is performed at strong coupling without the use of perturbation theory. The near-conformal scaling properties of light-front wavefunctions lead to a number of other predictions for QCD which are normally discussed in the context of perturbation theory, such as constituent counting scaling laws for structure functions at $x \to 1$, as well as the leading power fall-off of form factors and hard exclusive scattering amplitudes for QCD processes.

John Hiller, Dae Sung Hwang, Volodya Karmanov, and I have recently studied the analytic structure of light-front wave functions and its consequences for hadron form factors using the explicitly Lorentz-invariant formulation of the front form [71] where the normal to the light front is specified by a general null vector ω^μ. The resulting LFWFs have definite total angular momentum, are eigenstates of a *kinematic* angular momentum operator, and satisfy all Lorentz symmetries. They are analytic functions of the invariant mass squared of the constituents $M_0^2 = (\sum k^\mu)^2 = \sum \frac{k^2_{\perp i}+m_i^2}{x_i}$ and the light-cone momentum fractions $x_i = k_i \cdot \omega / p \cdot \omega$ multiplied by invariants constructed from the spin matrices, polarization vectors, and ω^μ. These properties can be explicitly verified using known nonperturbative eigensolutions of the Wick–Cutkosky model. The dependence of LFWFs on M_0^2 also agrees with the conformal form given above. The analysis implies that hadron form factors are analytic functions of Q^2 in agreement with dispersion theory and perturbative QCD.

The leading-twist PQCD predictions [33] for hard exclusive amplitudes are written in the factorized form as a convolution of hadron distribution amplitudes $\phi_I(x_i, Q)$ for each hadron I times the hard scattering amplitude T_H obtained by replacing each hadron with collinear on-shell quarks with light-front momentum fractions $x_i = k_i^+/P^+$. The hadron distribution amplitudes are obtained by integrating the $n-$parton valence light-front wavefunctions:

$$\phi(x_i, Q) = \int^Q \Pi_{i=1}^{n-1} d^2 k_{\perp i} \ \psi_{\rm val}(x_i, k_\perp).$$

Thus the distribution amplitudes are $L_z = 0$ projections of the LF wavefunction, and the sum of the spin projections of the valence quarks must equal the J_z of the parent hadron. Higher orbital angular momentum components lead to power-law suppressed exclusive amplitudes [33, 72]. Since quark masses can be neglected at leading twist in T_H, one has quark helicity conservation, and thus, finally, hadron-helicity conservation: the sum of initial hadron helicities equals the sum of final helicities. In particular, since the hadron-helicity violating Pauli form factor is computed from states with $\Delta L_z = \pm 1$, PQCD predicts $F_2(Q^2)/F_1(Q^2) \sim 1/Q^2$ [modulo logarithms]. A detailed analysis shows that the asymptotic fall-off takes the form $F_2(Q^2)/F_1(Q^2) \sim \log^2 Q^2/Q^2$ [73].

A model [71] incorporating the leading-twist perturbative QCD prediction is consistent with the JLab polarization transfer data [74] for the ratio of proton Pauli and Dirac form factors. Our analysis can also be extended to study the spin structure of scattering amplitudes at large transverse momentum and other processes which are dependent on the scaling and orbital angular momentum structure of light-front wavefunctions. Recently, Afanasev, Carlson, Chen, Vanderhaeghen, and I have shown that the interfering two-photon exchange contribution to elastic electron-proton scattering, including inelastic intermediate states, can account for the discrepancy between Rosenbluth and polarization data [75].

A crucial prediction of models for proton form factors is the relative phase of the timelike form factors, since this can be measured from the proton single spin symmetries in $e^+e^- \to p\bar{p}$ or $p\bar{p} \to \ell\bar{\ell}$ [76]. The Zemach radius of the proton is known to better than 2% from the comparison of hydrogen and muonium hyperfine splittings; this constraint needs to be incorporated into any analysis [77].

8 Applicability of PQCD and Conformal Symmetry to Hard Exclusive Processes

The PQCD/conformal symmetry predictions for hadron form factors are leading-twist predictions. The only mass parameter is the QCD scale, so the power-law predictions must be relevant – up to logarithms – even in the few GeV domain. Note also that the same PQCD couplings which enter hard exclusive reactions are tested in DGLAP evolution even at small Q^2. As noted above, the dimensional counting rules for form factors and exclusive processes have also been derived for conformal QCD using the AdS/CFT correspondence [54, 68].

In fact, there have been a remarkable number of empirical successes of PQCD predictions, including the scaling and angular dependence of $\gamma\gamma \to \pi^+\pi^-$, pion photoproduction, vector meson electroproduction, and the photon-to-pion transition form factor. A particularly dramatic example is deuteron photodisintegration which satisfies the predicted scaling law $[s^{11}\frac{d\sigma}{dt}(\gamma d \to pn) \sim \text{const}]$ at large $p_\perp$ and fixed CM angle [78] to remarkable high precision. Perturbative QCD predicts that only the small compact part of the light-front wavefunctions enter exclusive hard scattering processes, and that these hadronic fluctuations have diminished interactions in a nuclear target [24]. Evidence for QCD color transparency has been observed for quasi-elastic photoproduction [79] and proton-proton scattering [80]. In general, the PQCD scaling behavior can be modulated by resonances and heavy quark threshold phenomena [81] which can cause dramatic spin correlations [82] as well as novel color transparency effects [24, 80]. The approach to scaling in pion photoproduction: $[s^7\frac{d\sigma}{dt}(\gamma p \to n\pi^+) \sim \text{const}]$ and evidence for structure due to the strangeness threshold has recently been studied at Jefferson Laboratory [83].

Leading-order perturbative QCD predicts the empirical scaling of form factors and other hard exclusive amplitudes, but it typically underestimate the normalization The normalization of theoretical prediction involves questions of the shape of the hadron distribution amplitudes, the proper scale for the running coupling [84] as well as higher order corrections. In fact, as noted above, in the AdS/CFT analysis, hard scattering amplitudes which are normally of order α_s^p in PQCD appear as order $\alpha_s^{p/2}$ in the nonperturbative theory [53, 63].

The observation of conformal scaling behavior [85] in exclusive deuteron processes such as deuteron photoproduction [78] and the deuteron form factor [86] is particularly interesting. For example, at high Q^2 the deuteron form factor is sensitive to wavefunction configurations where all six quarks overlap within an impact separation $b_{\perp i} < \mathcal{O}(1/Q)$. In general, the six-quark wavefunction of a deuteron is a mixture of five different color-singlet states. The dominant color configuration at large distances corresponds to the usual proton-neutron bound state. However at small impact space separation, all five Fock color-singlet components eventually acquire equal weight, i.e., the deuteron wavefunction evolves to 80% "hidden color." The derivation of the evolution equation for the deuteron distribution amplitude and its leading anomalous dimension γ is given in Ref. [87]. The relatively large normalization of the deuteron form factor observed at large Q^2 [88], as well as the presence of two mass scales in the scaling behavior of the reduced deuteron form factor [85] $f_d(Q^2) = F_d(Q^2)/F^2(Q^2/4)$ suggests sizable hidden-color contributions in the deuteron wavefunction.

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